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AUTHOR Heller, Patricia; Finley, Fred
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ABSTRACT

In order to investigate the nature of students' prior knowledge of current electricity and how they applied their knowledge to different problems, 5 middle school science teachers and 11 elementary school teachers were given a written test that required them to: (1) predict what happens to the brightness of a bulb if a change is made to the circuit (a bulb is shorted or a second bulb is added in series or parallel); (2) compare the brightness of two bulbs in the same circuit; (3) compare the brightness of bulbs in different circuits; (4) compare the amount of current at different points in a series of parallel circuits; and (5) explain their reasoning for each question. The responses of the teachers were analyzed to determine the propositions they used for solving the problems and a matrix was formed of core propositions by subjects. From this matrix it was possible to determine the core propositions common to all teachers, as well as patterns of the different propositions held by different teachers. The results supported expectations about the nature of students' prior knowledge, how it is applied, and its application to the task of designing instruction for these students. (MVL)

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Variable Uses of Alternative Conceptions: A Case Study in Current Electricity

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by

Patricia Heller

and

Fred Finley

University of Minnesota

Department of Curriculum and Instruction

Minneapolis, Minnesota 55455

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INTRODUCTION

An important issue in science education today is how to design curriculum and instruction which changes students' "alternative" or "intuitive" conceptions about natural phenomena and promotes their ability to apply their knowledge in novel problem solving situations. Researchers agree that the first step in designing instruction that promotes such conceptual changes is to assess students' prior knowledge. Most prior knowledge assessments found in the misconception literature report the intuitive conceptions that are held in common by groups of students. Intuitive conceptions are logically consistent and strongly held conceptions which differ from the scientific conceptions we are attempting to teach. Linn (1986) has suggested that students' prior knowledge in any subject matter domain includes not only intuitive conceptions, but also ideas about which aspects of the intuitive conceptions are central to their thinking and which are peripheral. The central or "hard core ideas" are those ideas which learners persist in believing, even when evidence contradicting these ideas is available. The peripheral or "protective belt of ideas" are the ideas which learners readily change to defend the hard core.

However, attending only to students' hard core and protective belt ideas is not sufficient. Although students can be expected to exhibit these ideas, they can also be expected to apply these ideas in a variety of different ways as they solve unfamiliar problems. This expectation is based, in part, on the problem solving literature indicating that students' intellectual behavior while solving problems is adaptive -- that is, students apply their knowledge in various ways depending on the specific features of the problem that confronts them (Newell and Simon, 1972). A more complete picture of the students' prior knowledge and how they apply that knowledge is essential if instructional designs are to be effective. More specifically, instructional designers need to know answers to the following questions:

1. What conceptual knowledge do the students hold in common?
2. What are the variations in students' knowledge (i.e., what are the conceptions shared by only a few students)?
3. What are the variations in the ways students apply their knowledge to solve unfamiliar problems?

The answer to these questions allows the instructional designer to distinguish students' hard core ideas from their protective belt of ideas. This enables the designer to anticipate which ideas will be most resistant to change, and which ideas students will select or modify to defend the hard core ideas when they are challenged. The answers to these questions also allow the designer to identify: (1) what conditional knowledge (knowledge of when and where to apply certain conceptions) is missing, and (2) task features which cue the use of different conceptions to solve similar problems. With this information, the designer can plan activities that help students learn both the necessary conditional knowledge as well as the criteria for distinguishing relevant from irrelevant cues in selecting problem solutions.

The context for this study was the planning of a physical science course for inservice elementary school teachers. We were attempting to understand what the teachers knew about current electricity prior to instruction so that we could account for their knowledge in designing the instruction. This paper includes a description of the written pretest and analysis techniques used to assess the teachers' prior knowledge of current electricity (Method); a description of the similarities and differences in teachers' knowledge and variations in the ways teachers apply their knowledge to solve unfamiliar problems (Results); a description how that information was used to design instruction (Conclusions).

METHOD

The Subjects

The subjects were five middle school science teachers (grades 6 - 8) and eleven elementary school teachers (grades 2 - 5) from a small rural town in Minnesota. The teachers were enrolled in an integrated physics and science teaching methods course. Only five of the teachers had a physics course in their college backgrounds. They had 4 to 25 years of teaching experience (mean = 12 years).

The Current Electricity Pretest

The written pretest consisted of 13 problems with 6 of the problems comprising 2 or more parts. Most of the problems referred to a circuit diagram consisting of a battery, wires, and identical bulbs. These problems asked the teachers to (1) predict what happens to the brightness of a bulb if a change is made to the circuit (a bulb is shorted or a second bulb is added in series or parallel), (2) compare the brightness of two bulbs in the same circuit, (3) compare the brightness of bulbs in different circuits, or (4) compare the amount of current at different points in a series or parallel circuit (see Table 2 for a sample test problem). The teachers were asked to explain their reasoning for each problem.

The test was divided into two parts administered at two successive class sessions. Immediately after a teacher had completed each part, a researcher read through his or her responses and circled key words and phrases. The teacher was then asked to write what the word/phrase meant to them as they had used it in answering the associated problem. In general, words like current, conductor, resistance, energy, and power as well as phrases such as "the path of least resistance" and "energy is equally dispersed" were circled. The teachers wrote their explanations on the back of the test pages.

Analysis

To determine the teachers' propositional knowledge, the responses of all of the teachers to all of the pretest problems were examined using the following questions as a guide:

What is current?
What does a battery do?
What happens when current leaves the battery?
What happens when current encounters a bulb?
What happens when current encounters wire?
What happens when current encounters a junction?

These questions were not asked directly on the pretest. The teachers' propositional knowledge in these categories was inferred from the reasoning the teachers used to solve the problems.

From this first examination, a list of propositions for each question category was generated for the entire group of teachers in this study. For example, the propositions about what happens when current encounters a wire included:

Copper wires are excellent conductors of electricity.
Wires disperse (spread out) the current.

Wires simply conduct the current to the bulbs.
Wires use up or weaken the current (wires have resistance).
The longer the wire, the more current is used up.
Wires use up much less current than bulbs.

This list represents all of the propositions about the effect of wire on current that this group of teachers used to solve one or more of the pretest problems. An individual teacher could have one or more of these propositions.

For each teacher, the major statements or clauses in their pretest responses were numbered (e.g., P5a.6 means the 6th statement in response to problem 5a). Then each pretest was re-examined problem by problem. The researcher recorded all statement numbers which indicated that the given proposition was used by the teacher to answer the problems. At the same time, any previously unrecorded propositions for each teacher also were recorded. The accuracy of the results was checked by having a second researcher complete the procedure for 4 cases. Any differences in judgment were resolved by returning to the original statements. There were no disagreements on the propositional knowledge for any subject -- differences arose only in the number of student statements which supported the presence of a few of the propositions.

Finally, a matrix was formed of propositions by subjects. From this matrix it was possible to determine the propositional knowledge common to all teachers, as well as patterns of different sets of propositions held by different groups of teachers. To investigate individual variability in performance, a matrix of propositions by problems was formed for each subject. From this matrix, it was possible to determine which propositions were used consistently across similar problems, and which propositions were applied inconsistently. Two cases were dropped from the sample: One teacher did not answer enough problems on the pretest to determine her model, and one teacher, who was also an electrician, already had essentially the correct and complete current electricity model. The results of the analysis for the remaining 14 cases are reported below.

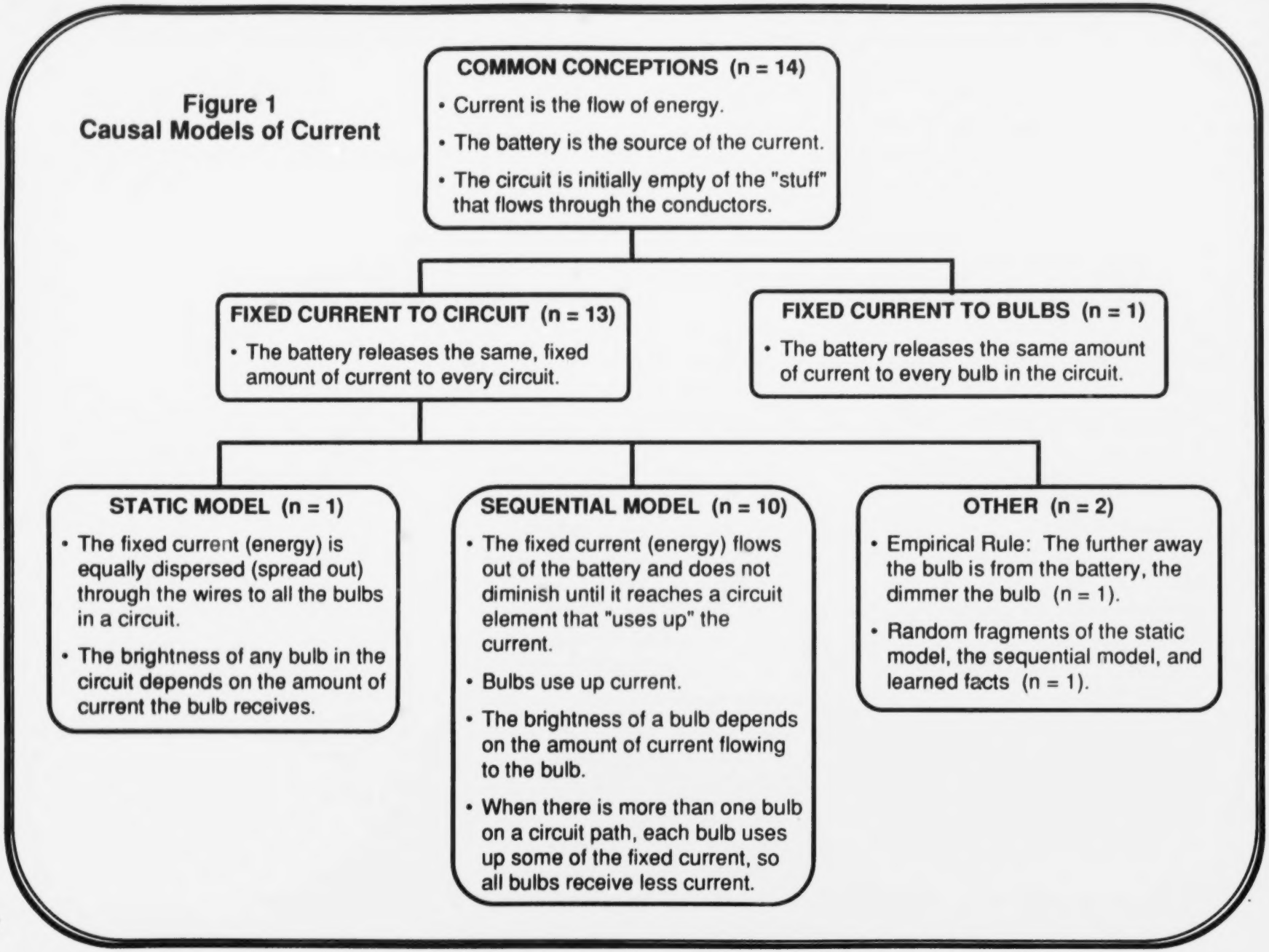
RESULTS

What Conceptual Knowledge do Teachers Have In Common?

The propositional knowledge common to all of the teachers was related to their beliefs about the nature of current and the function of the battery (see Figure 1). At first glance, these teachers seemed to have different views of the nature of current. That is, when asked specifically to define current, they provided imprecise and inconsistent notions about the relationship between current, electricity, charges, and energy. Regardless of their initial definitions, however, <u>all</u> of the teachers treated current as *energy* when they were asked to predict or compare the brightness of bulbs. This result is in agreement with other studies of secondary and college students (Osborne, 1981; Riley, Bee, and Mokwa, 1981; Von Rhoneck, 1983).

The teachers also believed that the battery is the source of the current, so the conductors in the circuit are initially empty of the "stuff" that flows through them (Tiberghien, 1983). They had two different notions about how much current a battery releases to different circuits. The majority of the teachers (n = 13) believed that a battery releases the same, fixed amount of current to every circuit. This result is consistent with other studies of secondary and college students (Closset, 1983; Cohen, Eylon, and Ganiel, 1983; Shipstone, 1984). Only one teacher had a different conception. She had apparently learned that for two bulbs in parallel, the potential difference across each bulb is the same, so each bulb receives the same current. She generalized this learned rule to the following:

Figure 1
Causal Models of Current


COMMON CONCEPTIONS (n = 14)
• Current is the flow of energy.
• The battery is the source of the current.
• The circuit is initially empty of the "stuff" that flows through the conductors.
FIXED CURRENT TO CIRCUIT (n = 13)
• The battery releases the same, fixed amount of current to every circuit.
FIXED CURRENT TO BULBS (n = 1)
• The battery releases the same amount of current to every bulb in the circuit.
STATIC MODEL (n = 1)
• The fixed current (energy) is equally dispersed (spread out) through the wires to all the bulbs in a circuit.
• The brightness of any bulb in the circuit depends on the amount of current the bulb receives.
SEQUENTIAL MODEL (n = 10)
• The fixed current (energy) flows out of the battery and does not diminish until it reaches a circuit element that "uses up" the current.
• Bulbs use up current.
• The brightness of a bulb depends on the amount of current flowing to the bulb.
• When there is more than one bulb on a circuit path, each bulb uses up some of the fixed current, so all bulbs receive less current.
OTHER (n = 2)
• Empirical Rule: The further away the bulb is from the battery, the dimmer the bulb (n = 1).
• Random fragments of the static model, the sequential model, and learned facts (n = 1).

> As long as the battery (volts) is the same, the same amount of energy is released to every *bulb* in the circuit.

She applied this rule to all the problems on the pretest; regardless of the circuit, all bulbs have the same brightness as a single bulb. This example is consistent with the study by Eylon and Helfman (1985), who found that physics students overgeneralize example problems in texts to apply to new problems.

Finally, there were two distinct models of what happens when the fixed current leaves the battery and encounters a bulb, one static and one dynamic (see Figure 1). The majority of the teachers (n = 10) used a dynamic model of current flow to answer most of the problems on the pretest. The dynamic model is defined by the four propositions below:

(1) The fixed current flows out of the battery and does not decrease or diminish until it reaches a circuit element that "uses up" some of the current.
(2) Bulbs use up current.
(3) The brightness of a bulb depends on the amount of current flowing to the bulb.
(4) When there is more than one bulb on a circuit path, each bulb uses up some of the fixed current, so all bulbs receive less current.

The first three propositions are commonly called the "sequential" model (Closset, 1983; Shipstone, 1984). The last proposition was included in the teachers' model because it was consistently used to answer several problems on the pretest. Notice that the first and last propositions are contradictory. The first proposition implies the lack of a feedback mechanism. The last proposition implies that there is some mechanism whereby current "knows" that other bulbs are in the circuit before the current reaches the first bulb. This feedback mechanism was not defined by any of the teachers.

In the sequential model of current, there is an implicit dependence on time -- that is, the current flows from the battery and is not modified until it reaches a component that consumes current. In contrast, the static model of current ignores the initial current flow and focuses instead on the final state of the circuit, as defined by the two propositions below:

(1) The fixed current (energy) is equally dispersed through the wires and to all the bulbs in a circuit.
(2) The brightness of any bulb in the circuit depends on the amount of energy the bulb receives.

The static model leads to the prediction that the current is the same at all points in a circuit, and all bulbs in a circuit (series or parallel) are the same brightness because they each receive the same amount of current. Only one of these thirteen teachers consistently applied the static model to answer all the problems on the pretest.

Two teachers in the sample could not be classified as using the static or sequential model of current. One teacher seemed to have an incomplete dynamic model of current flow to bulbs. He believed that a fixed amount of current flows from both ends of the battery. However, he appeared to use the following "empirical" rule to answer the problems on the pretest: The further away the bulb is from the battery, the dimmer the bulb. This rule was not tied to any stated belief that either the bulbs or the wires use up current. The other teacher seemed to use random fragments of learned knowledge, the static model, and the dynamic model to answer the problems. He did not appear to have any consistent model of current flow. For example, he said that two bulbs in series are the same brightness because "there is the same amount of DC current entering the bulbs and leaving the bulbs." However, he said that the current at a point near the battery is the same before

and after the second bulb is added in series because "current does not diminish greatly until it passes through more resistance (copper wire and filament)."

What Are the Variations in Teachers' Knowledge?

The analysis in the preceding section indicated that, for the majority of the teachers (n = 10), the common conceptions of current consisted of eight propositions about the nature of current, the function of the battery, and what happens to current when it encounters a bulb (see Figure 1). The variations in teachers' knowledge related to (1) the direction of current, (2) the effect of wires on current, and (3) what happens when current encounters a junction. The different conceptions teachers held about these three aspects of current electricity resulted in large variations in their predictions of the brightness of bulbs in series, parallel and short circuits, as described below.

Direction of Current

Teachers exhibited three different conceptions about the direction of current: current flows from both poles of the battery, from the negative to the positive pole, or from the positive to the negative pole. Consequently, there were three different predictions of the brightness of two bulbs in series (see Table 1). If current flows from both battery terminals (n = 1), then the two bulbs are the same brightness because they each receive the same amount of current (Sequential 3 in Table 1). If current flows in one direction (n = 9), however, then the second bulb encountered is dimmer than the first bulb because some of the current is used up by the first bulb. Since there are two directions current can flow, there are two different predictions: if current flows from the positive terminal of the battery, bulb A is brighter than bulb B; if current flows from the negative terminal, bulb B is brighter than bulb A (Sequential 2 and 3 in Table 1).

Effect of Wires on Current

Teachers also had different conceptions of the effect of wires on current: wires simply conduct the current to the bulbs (n = 6), or wires use up current (n = 4). The teachers who believed that wires use up current tended to generate the rule, "the farther the bulb is from the battery terminal, the dimmer the bulb" (see Sequential 2 in Table 1). For parallel circuits, the application of this rule resulted in different predictions for the brightness of two parallel bulbs. That is, if wires use up current, then the bulb further from the battery will be dimmer than the closer bulb. On the other hand, if wires simply conduct current to bulbs, then all parallel bulbs will be the same brightness.

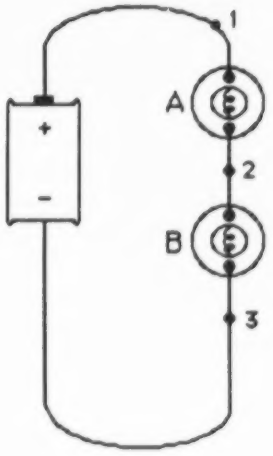
Current at Junctions

Finally, teachers held a surprisingly large number of different conceptions about what happens to current when it encounters a junction (see Table 2). Of the eight different junction models, only four have current dividing or splitting at a junction; in the remaining models current division is not recognized. These different models often resulted in different predictions about the brightness of parallel bulbs. For example, if slightly less current flows down the closer path, then bulb A will be dimmer than bulb B (Model 5 in Table 2). On the other hand, if the current divides equally at a junction, then bulb A will be the same brightness as bulb B (Models 7 and 8 in Table 2).

What Are the Variations in the Ways Teachers Apply Their Knowledge to Solve Problems?

There were many inconsistencies in the way individual teachers applied their knowledge to solve problems. In fact, of the eight sequential model propositions teachers had in common, only

Table 1
Example of Series Circuit Explanations



12a. How does the brightness of bulb A compare with the brightness of bulb B? Explain your reasoning.

12b. Compare the amount of current at points 1, 2 and 3. Explain your reasoning.

Sequential 1: (Current flows from + to - pole)

Bulb B is dimmer than bulb A because bulb A uses up some of the current, so less current flows to bulb B. The current decreases from point 1 to point 3 (1 > 2 > 3).

Sequential 2: (Current flows from - to + pole and wires use up current)

Bulb A is dimmer than bulb B because it is farther away from the battery, so some current is used up by the wires and bulb B. The current decreases from point 3 to point 1 (3 > 2 > 1).

Sequential 3: (Current flows from both poles of the battery)

Bulbs A and B are the same brightness because they receive the same current from the + and - ends of the battery. The current at points 1 and 3 are equal; the current at point 2 is less (1 = 3 > 2).

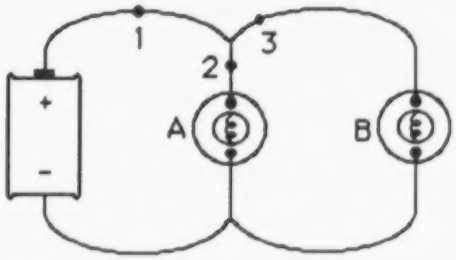
Adjusted Sequential 1:

The total current decreases from points 1 to 3 because the bulbs are using up current (1 > 2 > 3). But the bulbs are the same brightness because identical bulbs use up the same amount of current.

Adjusted Sequential 2:

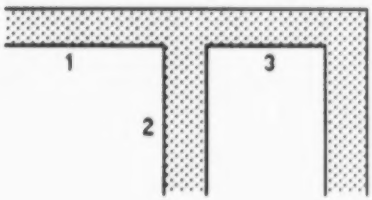
Bulbs A and B are the same brightness because the (fixed) current is equally dispersed to both bulbs. But the current decreases because the bulbs use up the current (1 > 2 > 3).

Table 2
Models of Junctions in Parallel Circuits



5c. Compare the amount of current in the wires at points 1, 2, and 3. Explain your reasoning.

Junction Not Recognized



1. The current is the same at all three points (1 = 2 = 3) because the current has not yet reached the bulbs (or is not hindered by any bulbs as it returns to the battery).

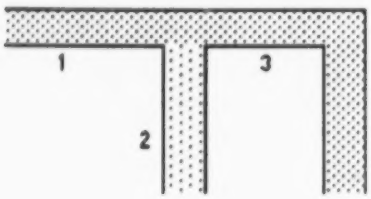
2. The current is largest at point 2 because it is closest to the negative pole. The current at point 3 is greater than at point 1 because of the distance to the negative pole. Point 1 is carrying the least amount because of the bulbs A and B using up the electricity (2 > 3 >1).

3. The current at points 1 and 2 are equal because it has not yet reached the bulb. The current at point 3 is least because the current has been used in passing through bulbs A and B (1 = 2 > 3).

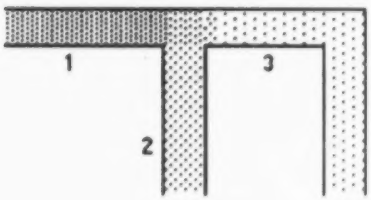
4. The current at points 1 and 2 are equal because it has not yet reached bulb A. The current at point 3 is least because the current flows around the circuit with bulb A before it flows through the circuit with bulb B (1 = 2 > 3)

Table 2 (continued)
Models of Junctions in Parallel Circuits

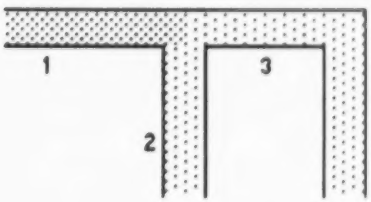
Current at Junction Divides



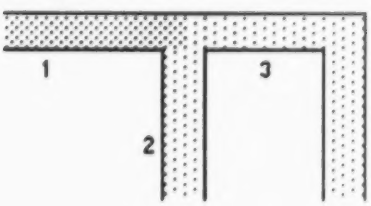
5. The current at points 1 and 3 are about equal. Slightly less current flows down the path to point 2.
(1 = 3 > 2)



6. The current at point 1 is largest because it has not yet split. The current at point 2 is larger than the current at point 3 because more current flows through the closer path (1 = 2 + 3; 2 > 3).



7. Points 2 and 3 would each have half of the current at point 1 because it would divide evenly when the split occurs.
(1 = 2 + 3; 2 = 3)



8. The current at point 1 is the sum of the currents at points 2 and 3. The current at points 2 and 3 is the same because current follows the path of least resistance. Since the paths have the same resistance, the current through each path is the same.
(1 = 2 + 3; 2 = 3)

five appeared to be central to their reasoning across pretest problems. These five internally consistent propositions were never modified or compromised in any way:

(1) Current is the flow of energy.
(2) The battery is the source of the current.
(3) The circuit is initially empty of the "stuff" that flows through the conductors.
(4) The battery releases the same, fixed amount of current to every circuit.
(5) Bulbs use up current.

This result suggests that these five propositions comprise the hard core of ideas about current electricity for these teachers. Inconsistent applications of the protective belt ideas as well as a lack of conditional knowledge were the sources of individual variations in problem solving performance, as described below.

Changing Protective Belt Ideas

One of the most striking examples of individual variability occurred with the five teachers who knew that two bulbs in series glow with the the same brightness (like Christmas tree lights). Since this observation contradicts the predictions of the sequential model (e.g., Sequential 1, 2 and 3 on Table 1), the teachers adjusted their explanations for the equal brightness of the two bulbs. Two kinds of adjustments were made: (1) a change in one of the sequential-model propositions, or (2) a temporary switch to a static-model type of explanation. Two teachers made the first kind of adjustment. They changed their conception about what causes the brightness of a bulb from "brightness depends on the amount of current flowing *to* the bulb" to "brightness depends on the amount of current *used up* by the bulb". Since identical bulbs use up identical amounts of current, the two bulbs in series are the same brightness (Adjusted Sequential 1 in Table 1). For the other problems on the pretest, however, these teachers reverted back to their first, sequential model conception of what causes the brightness of a bulb.

The other three teachers switched to a static-model type of explanation to account for the equal brightness of the bulbs. On the first series circuit problem (which did not ask for a comparison of the current at different points in the circuit), they used the proposition that the bulbs are the same brightness because the current is equally dispersed to (or shared by) the two bulbs. However, on the second series circuit problem (which asked for a comparison of the current before, between, and after the bulbs) these teachers did notice the contradiction between their static-model explanation for the equal brightness of the bulbs and their sequential-model beliefs . Using the sequential model, they all predicted that the current decreases from point 1 to point 3 as it is used up by the bulbs. One teacher then went back and crossed out his static-model explanation for the equal brightness of the bulbs and used the sequential model to predict that bulb A is brighter than bulb B. Similarly, another teacher temporized: "In *this* series circuit, bulb A will be slightly brighter than bulb B??" The third teacher simply said, "I know they are the same brightness - why?"

These results support the earlier suggestion that the proposition, "Bulbs use up current (energy)," is a hard-core conception which persists even when contradictory evidence of the equal brightness of series bulbs is available. On the other hand, for two teachers the proposition, "The brightness of a bulb depends on the amount of current flowing to the bulb," appears to be a protective belt conception, since they were willing to change this notion to defend the hard core conception. The fact that three teachers initially switched to a static-model type of explanation to explain the equal brightness of series bulbs suggests that the time-dependent portion of the sequential model, "Current does not diminish until it reaches a circuit element that uses up the current," may also be a protective belt conception. These teachers were willing to suspend or ignore the time-dependent portion of their current model and adopt a contradictory time-independent, static conception to explain the equal brightness of the series bulbs. They were not,

however, willing to change or modify their hard-core conception that bulbs use up current, even when they noticed the contradiction. On the contrary, two teachers were ready to abandon their observation of equal brightness rather than change their hard core conception.

Contradictory Protective Belt Ideas

The fact that two contradictory propositions, a time-dependent proposition and a time-independent proposition, are included in teachers' modified sequential model of current supports the hypothesis that the time-dependent conceptions of current are part of the protective belt of ideas (see Figure 1).

(1) Time-dependent proposition: the (fixed) current flows out of the battery and does not diminish until it reaches a bulb that "uses up" some of the current.
(2) Time-independent proposition: when there is more than one bulb in a circuit path, each bulb uses up some of the (fixed) current, so all bulbs receive less current.

These contradictory propositions generated inconsistent patterns of explanations, as illustrated in Table 3. All ten sequential-model teachers used the time-dependent proposition to predict that current is not affected by the addition of a second series bulb (Problem 4c on Table 3). Use of this proposition in Problem 4a would lead to the prediction that, when the second series bulb is added, the first bulb stays the same brightness because it receives the same amount of current. Instead, *all* teachers used the time-independent proposition to predict that the first bulb dims when the second series bulb is added (Problem 4a in Table 3). They failed to notice that the proposition they used to explain one situation contradicted the proposition used to explain another related situation. This lack of consistency has also been found in studies of students' intuitive conceptions in mechanics (for example, Champagne, Gunstone, and Klopfer, 1985; McDermott, 1984).

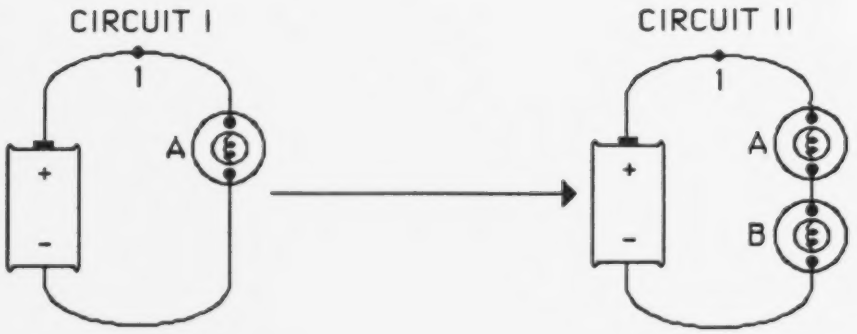
In general, different problems cued different, contradictory conceptions about the time-dependent nature of current. With few exceptions, the four problems on the pretest that asked for either a comparison of the brightness of a bulb before and after a change or the comparison of the brightness of a bulb in different circuits cued the use of a time-independent, static-model type of explanation -- i.e., an explanation that focuses on the final state of the circuit and ignores the time-dependence of current flow. On the other hand, the six problems which required a comparison of current at different points in the circuit cued the use of the time-dependent conception of current.

Missing Conditional Knowledge

The third source of individual variation across problems was evident in the students' responses to the parallel and short circuit problems. For example, only five teachers consistently used one junction model in all the parallel circuit problems (Models 2, 3, 6, 7 and 8 respectively). The remaining five teachers used two or more junction models for the different problems. They seemed to be influenced by their spatial perception of the different parallel circuits. For example, one teacher (who did not believe that wires use up current) predicted that two bulbs in parallel are the same brightness because the current divides equally at the junction (Model 7 in Table 2). For three bulbs in parallel, however, he predicted that the bulbs are successively dimmer as the distance from the battery increases because more current flows down the first path than the second path, and more current flows down the second path than the third path (Model 6 in Table 2). Apparently, the added "distance" in the three-bulb parallel circuit prompted a different model of what happens at a junction.

Similarly, these teachers were influenced by *where* the junction occurs, at the battery terminal, at the bulb socket terminal, or at a wire splice, as illustrated in Example 1 in Table 4. This teacher predicted that bulb A is brighter in Circuits I and III because the junction occurs and the current splits before it reaches bulb B. He treated Circuit II as a series circuit because he did not recognize

Table 3
Inconsistent Dynamic Model Explanations for Series Circuit Questions



4a. What happens to the brightness of bulb A when a second identical bulb is added to the circuit as shown? Explain your reasoning.

Bulb A dims because the second bulb uses up some of the (fixed) current.

4b. In circuit II, how does the brightness of bulb A compare to the brightness of bulb B? Explain your reasoning.

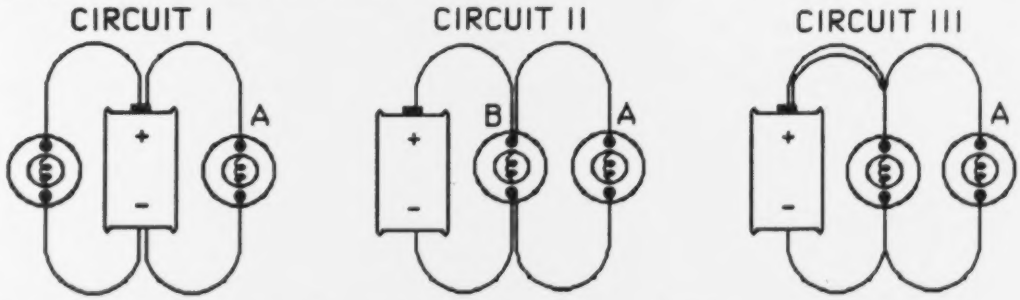
Bulb B is dimmer than bulb A because bulb A uses up some of the current, so less current flows to bulb B.

4c. Compare the amount of current in the wire at point 1 before and after the second bulb is added (i.e., In which circuit is there the most current flowing through the battery, or is the current the same?) Explain your reasoning.

The current is the same in both circuits. No current is being used by the bulbs at point 1, so the number of bulbs does not influence the current at this point.

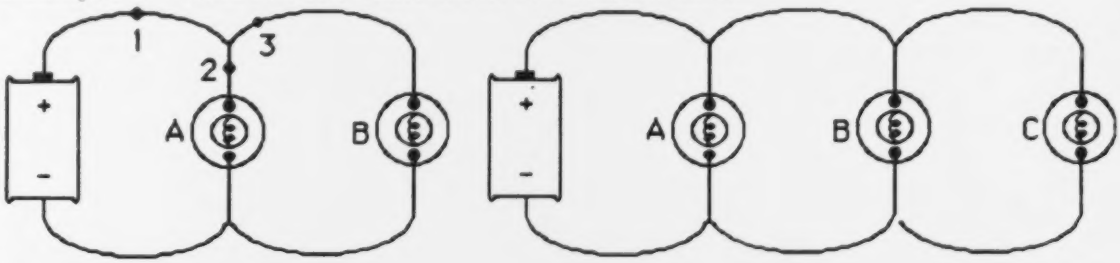
Table 4
Examples of Individual Variability Across Similar Problems

Example 1: Different Junction Models



6a. Bulb A is the same brightness in Circuits I and III because the current splits before reaching either bulb. In Circuit II bulb A is dimmer because some of the current is lost to bulb B before it reaches bulb A.

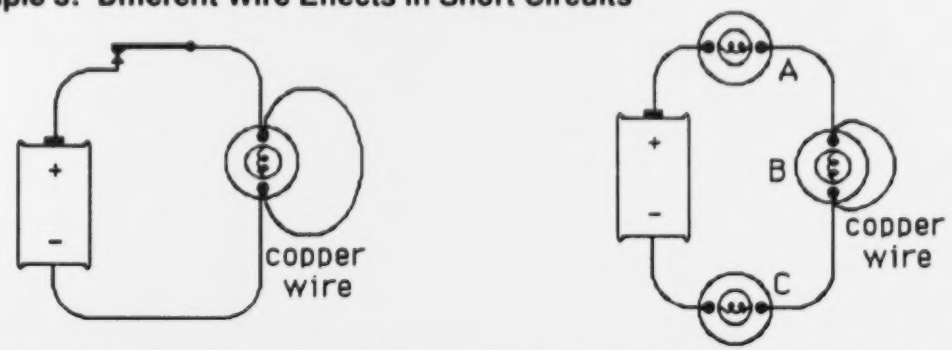
Example 2: Different Wire Effects in Parallel Circuits



5b. Bulb A is the same brightness as bulb B because the current is equally divided between the two bulbs.

11. Bulb A is brighter than bulb B, and bulb B is brighter than C because more and more current is used up traveling the extra distance to each bulb.

Example 3: Different Wire Effects in Short Circuits



2. The bulb dims because some of the current is used up traveling the extra distance through the copper wire.

7. Bulb B gets brighter because copper is an excellent conductor of electricity, so it increases the flow of current.

the junction at the bulb socket terminal. The variability in these five teachers' use of different junction models suggests that they may have been constructing propositions on a problem-by-problem basis.

The teachers exhibited similar inconsistencies in their use of propositions about the effect of wires on current in parallel and short circuits. Different problem tasks seemed to cue the use of different propositions. For example, one teacher ignored the effect of wires on current in the two-bulb parallel circuit. For the three-bulb parallel circuit, however, he predicted that each bulb would be successively dimmer because "more current is used in traveling the extra distance to the bulbs" (Example 2 in Table 4). Similarly, two teachers predicted that a shorted bulb dims in a one-bulb circuit. The three-bulb series circuit, however, appeared to cue a new, learned proposition, "copper is an excellent conductor of electricity," which resulted in a different prediction about the brightness of the shorted bulb (Example 3 in Table 4).

Apparently, many teachers did not know under what conditions to apply either their junction or their wire propositions. For example, the teachers who believed that wires use up current did not know how long a wire has to be before there is a noticeable effect on the current. Consequently, they often gave inconsistent answers to similar problems on the pretest. This type of error has been noted in many problem solving contexts (see, for example, Reif, 1985).

CONCLUSIONS

The results of this study supported our expectations about the nature of students' prior knowledge and how it is applied. Most of the elementary and middle school teachers in this study shared a common set of propositions that made up a coherent, but incorrect and contradictory sequential model of current flow. The core of the teachers beliefs were that:

> The battery is the source of current. It releases a fixed amount of current (energy) that circulates around the circuit. This fixed current is not modified until it reaches a circuit component that consumes the current. The current is then successively consumed by each component of the circuit. Bulbs use up or consume current. The brightness of a bulb depends on the amount of current flowing to the bulb. When there is more than one bulb on a circuit path, each bulb consumes some of the fixed current, so all bulbs receive less current.

If this set of propositions had comprised *all* the teachers' knowledge, and if they had applied this knowledge consistently, then there would have been a limited variety of responses. Yet this was not the case. There was a very wide range of answers to the problems on the pretest. The variability in their predictions arose from several sources:

1. Individual teachers had different conceptions about the direction of current flow, the effect of wires on current, and what happens to current at a junction.

2. Teachers adjusted their protective belt propositions to account for previously learned facts that contradicted the predictions of their hard core conceptions of current.

3. Different problem types cued the use of different, contradictory protective belt conceptions about the time-dependent nature of current flow, which lead to unrecognized inconsistencies in their answers to several problems

4. Different contextual and perceptual features of the problem tended to sway their judgment about which junction or wire propositions to apply. That is, teachers often did not appear to have the necessary conditional knowledge to know when to apply or not apply certain propositions.

The theoretical importance of recognizing these sources of variation is that much of the conceptual change literature and the more narrowly focused research on misconceptions has implied that understanding the intuitive or alternative conceptions of students provides a sufficient basis for predicting their performance. Knowing that teachers have a common set of propositions is necessary but not sufficient. It appears that in addition to a common core, people also have ideas of their own that are important to their performance and that they do not simply apply their ideas in a mechanical manner. They adapt their thinking to the problem at hand, even when this means that their solution to one problem was inconsistent with their solutions to other problems and that different propositions result in unrecognized contradictions within a problem.

The practical implication of these findings is that the process of designing science curriculum and instruction becomes more difficult. If we are going to attempt to account for students' prior knowledge as a basis for our designs, we need to learn to account for the variations in students knowledge as well as the commonalties. While this is difficult, it is not impossible and it may substantially improve our instructional designs. For example, in the present case, the results of this study were applied to the task of designing instruction in current electricity.

We used the conceptual change model of Posner, Strike, Hewson and Gertzog (1982) to plan a sequence of activities designed to change students hard core ideas about the nature of current flow. The sequence of activities was based on the introduction of two competing fluid flow analogies. One of these reflected the common set of propositions of their sequential current model and the other reflected a correct model. The teachers were guided through a series of experiments to decide which model consistently accounted for all of the observed facts. That is, the epistemological commitment to internal consistency was specifically built into the instructional sequence. We also selected instructional methodologies that help learners recognize inconsistencies in their reasoning and consider alternatives. For example, the teachers were placed in small cooperative groups so they could compare and discuss their different predictions, the observations, and their subsequent conclusions. The instructors' role included challenging the reasoning of the groups, and occasional whole-class discussions allowed the groups to compare reasoning and conclusions and consider additional alternatives.

Within this broad framework, we used our results of the sources of variability in performance on the pretest to help us select and design specific activities to incorporate in the instructional sequence. For example, we designed activities to account for specific correct and incorrect conceptions that the teachers brought to the instruction. One such activity required teachers to predict, discuss and measure what happens to the current at a junction of wires. We also designed activities to help students acquire necessary conditional knowledge about junctions and the effect of wire on current. For example, the junction activities included experiments to determine if the location of a junction (at the battery terminal, at the bulb socket, or at a wire splice) affects how the current divides. Teachers also did experiments to determine how long connecting wires need to be to observe a perceptible dimming of the bulbs, and how long a "shorting" wire must be to observe a dim glow of the shorted bulb.

The pretest results indicated that different problem types cued the use of different, contradictory conceptions about the time-dependent nature of current flow in the problem solution: problems which asked for the comparison of the brightness of bulbs cued the use of a time-independent conception, and problems which asked for a comparison of the amount of current cued the use of a time-dependent conception. To help teachers resolve the issue of the time-dependent nature of current, all activities required the teachers to compare both the brightness of

the bulbs and the current at different points in the circuit. In addition, teachers were required to trace the current path both in the actual circuit and in the circuit diagrams. Tracing the path of the current helps teachers learn to cue on the important distinguishing characteristic of series and parallel circuits, the presence or absence of a junction. Moreover, tracing the current path in a series circuit helps teachers recognize that the current must flow successively through the bulbs, so the current cannot be equally dispersed to (or shared by) the bulbs.

Finally, we planned a sequence of activities to help teachers develop the criteria for differentiating relevant from irrelevant cues when selecting a solution to a current electricity problem. We designed a sequence of guided experiments for the construction of a set of qualitative current electricity rules about what happens to the total current in the circuit and the brightness of each bulb when (1) a bulb is added to or removed from a circuit path, (2) a bulb is shorted, (3) a path of one or more bulbs is added parallel to the battery, and (4) a path of one or more bulbs is added that is not parallel to the battery. The "If . . . , then . . . ." form of these rules specified the criteria or conditions for selecting and applying different propositions to solve a problem. Teachers then practiced solving problems by selecting and then testing the applicability of different rules.

In short, the results of this study provided an extensive and precise basis for the detailed planning of instruction. Our judgment is that the knowledge we gained from analyzing the sources of variability in performance on a problem solving pretest was invaluable in developing the instruction and in the insights that we were able to employ as we interacted with the teachers during the actual teaching. This judgment is supported by the teachers reactions to the instruction and by our preliminary analyses of the results of a posttest. There were substantial changes in students understanding of current electricity and students became far more capable of predicting and explaining what happens to the total current in the circuit and the brightness of bulbs in a variety of circuits.

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